Chapter 1
Introduction

1-1. General

Roller compacted concrete (RCC) dams are designed in accordance with EM 1110-2-2200. The proportions of the RCC dam are derived by stability analysis in a manner identical to that for a conventional concrete gravity dam and are governed by the static forces to be resisted and not by the dynamic forces generated during seismic activity. After the geometric proportions are determined based on the static loads a dynamic analysis is conducted. Zones requiring superior RCC mixes are established, and vibratory compaction methods and joint preparation methods which affect the RCC tensile strength are also established based on the criteria provided in this engineer pamphlet (EP).

1-2. References

Required and related publications are listed in Appendix A.

1-3. Explanation of Terms

Abbreviations, symbols, and notations used throughout this EP are explained in the glossary.

1-4. Background

Basic criteria and guidance for the design of RCC dams are provided in EM 1110-2-2200. ER 1110-2-1806 provides guidance on analysis methods and procedures for new designs and an investigative program for existing dams. ETL 1110-2-301 gives additional information on specifying earthquake ground motions for a particular site. ETL 1110-2-303 provides guidance on finite element dynamic analysis methods and on evaluating the severity of cracking based on tensile stresses from the linear analysis. EM 1110-2-2006 provides guidance concerning RCC usage and mix design.

1-5. Design Philosophy

a. Response spectrum analysis. The nonlinearities associated with concrete behavior under seismic loading are difficult to assess and beyond practical analyzing capabilities of most design offices. Procedures which permit the use of a linear-elastic type of dynamic analysis adjusted to provide a reasonable but conservative approximation of the nonlinear behavior are adequate in almost all design situations. The philosophy of design followed in this EP will be to establish the procedures applicable to the majority of design situations. This consists of providing in some detail the requirements for performing the linear-elastic response spectrum analysis and the criteria for evaluating the results.

b. Refined analyses. For the few occasions where this approach does not produce a satisfactory design or where an existing dam does not satisfy criteria, the designer is then advised to pursue the more refined analysis methods. Should the even more complex nonlinear analysis become necessary, it should be performed under the guidance of a recognized expert in this specialized field and should only be undertaken with approval of CECW-ED.

1-6. Design Earthquakes

The linear-elastic response spectrum method of analysis is the simplest dynamic analysis method and provides adequate results for most designs. The ground motion is usually defined by design response spectra scaled to peak ground accelerations (PGA) for the two design earthquakes described below.

a. Operating basis earthquake. The operating basis earthquake (OBE) is defined as the earthquake producing the greatest level of ground motion that is likely to occur at the site during the economic life of the dam.

b. Maximum credible earthquake. The maximum credible earthquake (MCE) is defined as the earthquake which produces the greatest level of ground motion at the site as a result of the largest magnitude earthquake that could reasonably occur along the recognized faults or within a particular seismic source.

c. Types of design spectra. Design response spectra for the OBE are usually developed using a probabilistic approach, and design response spectra for the MCE are developed using a deterministic approach. Design response spectra are further classified into two types: (1) site-specific or (2) standard. The seismic zone location of the site, the height of the dam, and the proximity to active faults are the factors used to determine if it is necessary to develop a site-specific design response spectra or if the standard spectra may be used in the dynamic analysis. When standard design response spectra are acceptable, Chapter 5 provides the appropriate spectra along with the PGA values to be used for scaling. These standard design spectra are based on the mean level of the ground motion parameters for the records selected in the development of the standard spectra.

d. Ground motion time histories. The more refined analysis methods require a ground motion time history representation of the design earthquakes. These may be developed using actual past earthquake ground motion records, synthetically, or by modifying an actual record. Ground motion time histories are developed so their response spectrum closely matches the site-specific design response spectrum.

1-7. Acceptance Criteria

a. Cracking of RCC. The ground motion that is produced during a seismic event can cause cracks to occur in an RCC dam. As cracking progresses, serviceability is eventually impaired. If ground shaking is extremely severe, or if strong ground shaking combines with a foundation fault displacement, it is conceivable that continued propagation of the system of cracks could eventually lead to a failure mechanism where the dam is no longer capable of containing the pool. This EP establishes acceptance criteria which maintain serviceability during an OBE, and provide a reasonable safety factor against developing a failure mechanism during a MCE. Because of the complexity and the great number of variables involved in seismic design, the EP criteria should be supplemented with the judgment of structural engineers experienced in seismic design.

b. Direct tensile strength. The direct tensile strength of the RCC is the design parameter used for establishing the acceptance criteria. Unlike conventional concrete, tensile strength of RCC depends on mix consistency and placement and compaction methods as well as mix proportions. Tensile strength of both the lift joint and the parent concrete shall be determined from cores taken from test fill placements for new dam design and from the in-place RCC for existing dams. Although splitting tensile tests may be used, the test results shall be adjusted to reflect direct tensile strength. From the direct tensile strength, the allowable design tensile stresses shall be established for both lift joints and parent concrete by applying adjustment factors to account for high strain rate associated with dynamic loading and certain nonlinear characteristics of the stress/strain curve. Adjustment factors shall be selected to maintain serviceability during an OBE and to produce a reasonable safety factor for a MCE.

1-8. Important Factors

Discussed below are recommendations regarding factors which are important because they have a significant impact on the dynamic response. Recommendations that differ from those contained in ETL 1110-2-303 and ER 1110-2-1806 are identified.

a. Effective damping. The material and radiation damping of the foundation contribute significantly to the damping of the combined dam-foundation system, and must be considered in the analysis. This requires calculating an effective viscous damping ratio to reflect the damping contribution of both the dam and the foundation. This will result in a considerably higher damping ratio for a foundation having a very low modulus than the damping ratio used previously.

b. Hydrodynamic effect. Added mass shall be calculated using standard hydrodynamic pressure function curves which consider compressibility of the water, stiffness characteristics of the dam, and reservoir bottom absorption (Fenves and Chopra 1986). Appendix D provides an example showing the required procedure.

c. Mode combination methods. The complete quadratic combination method (CQC) of combining modes shall be used for final design of dams under critical seismic design conditions and for evaluation of existing dams. Critical conditions are considered to exist when site-specific design response spectra are required by this EP. Either the square root of the sum of the squares method (SRSS) or the CQC method is acceptable for all preliminary designs and for final designs under noncritical seismic conditions. Since the modal frequencies are fairly well separated in gravity dams, the simpler SRSS method produces adequate results which are in balance with the general level of precision required for preliminary or noncritical analyses.

d. Seismic zone map. The seismic zone map, Figure 5-1, shall be used in the dynamic stress analysis phase of the seismic design. The peak ground accelerations for use in scaling standard design response spectra are contained in Table 5-2 and are based on the zone map. The seismic zone maps and the seismic coefficients contained in ER 1110-2-1806 shall be used only in the stability analysis phase of seismic design.

1-9. Analysis Methods and Procedure

In general a dynamic stress analysis shall be performed, and the results shall be evaluated to determine if the response of the RCC dam to the design earthquakes is acceptable. If the response is not acceptable, the design of a new dam may be modified and reanalyzed using the same analysis method, or a more refined analysis method may be employed. For an existing dam, progressively more refined methods of analysis are employed.

a. Method attributes. There are four attributes that characterize a particular dynamic analysis method.

(1) Material behavior. Options are (a) linear-elastic or (b) nonlinear behavior.

(2) Design earthquake definition. Options are (a) design response spectrum or (b) time history ground motion record input.

(3) Dimensional representation. Options are (a) two-dimensional representation or (b) three-dimensional representation.

(4) Model configuration. Options are (a) Chopra's "standardized" model, (b) composite finite element-equivalent mass system model, or (c) finite element-substructure model.

b. Computer programs. Various computer programs are available which are identified with certain analysis methods. Also, Chopra's Simplified Method may be either hand-calculated or done by a computer program. Some computer programs, such as the general purpose finite element programs, allow the attribute options to be changed so that one of several possible methods may be employed for the dynamic analysis. This often allows a transition to a more refined method without necessarily abandoning all the previous computer model input effort. Other computer programs, such as the EAGD-84 program, and Chopra's Simplified Method are single method programs since they have fixed attributes. Chapter 8 discusses dynamic analysis methods in more detail.

c. Preliminary and final design. The two-dimensional, linear-elastic, response spectrum method shall be used for the preliminary design analysis. Either Chopra's Simplified Method or a general-purpose finite element program shall be employed depending on the design conditions. The simplest final design analysis utilizes a composite finite element-equivalent mass system model and general-purpose finite element program.

1-10. Coordination

A fully coordinated team of structural engineers, geotechnical and materials engineers, geologists, and seismologists should ensure that all factors relevant to the dynamic analysis are correct and that the results of the analysis are properly evaluated. Some of the critical analysis and design aspects requiring coordination are discussed below.

a. Design response spectra. Developing site-specific design response spectra when required.

b. Tensile strength of RCC. Obtaining representative cores from test-fill placements for new dams or from the in-place concrete for existing dams for use in determining the direct tensile strength and dynamic tensile strength of both the lift joints and the parent RCC.

c. Foundation properties. Obtaining exploratory corings and evaluating tests to determine the foundation deformation modulus and other foundation properties.

d. Foundation fault displacement. Evaluating geoseismic conditions at the site to determine if foundation fault displacement is possible, and to map the location, strike, and dip of the potential faults.